Spin transport and dynamics in magnetic insulator/metal systems

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Appendix A

Overview of thermo-electric and magnetic effects

Many different interactions of electric/magnetic fields and temperature gradients with electrons are known. Well known effects caused by these interactions are for example the Hall effect, the Seebeck effect and the Peltier effect. Analogous effects have been observed in the field of spintronics, where the spin transport is shown to be influenced by electric/magnetic fields and temperature gradients, leading to effects such as the spin-Hall effect, spin-Seebeck effect and spin-Peltier effect.

As there are many effects, sometimes having similar names but different origin, or similar origin but different outcomes, this section gives an overview of some of them to help the reader find its way in the jungle of thermo-electric/magnetic effects. Note that it is impossible to list all known thermo-electric/magnetic effects; only a selection of them is given. Most of the listed effects are chosen as they are somehow related to the work presented in this thesis. Nevertheless, they are generally present in many different systems in different fields of physics, making it worth to be aware of their existence.

Of all listed effects, a short description is given as well as an equation directly showing the dependency on the parameters of interest. Finally a schematic of each effect is shown. In these figures, the red marked vector shows the result of the described effect[1], in the presence of the black and blue marked vector(s); the blue marked vector defines the driving force of the effect. For some effects to be present the material itself needs to be magnetic, in the schematic of these effects the material is gray-colored. Temperature gradients are visualized by a gradient in color from red (=hot) to white (=cold), in addition to any drawn vector. Furthermore, in the shown figures the drawn vector for the spin-current J_s points towards the spin-current direction, whereby the spin-polarization direction is chosen to be always (anti-)parallel to the $\hat{z}$-axis (which points upwards).

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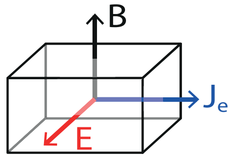
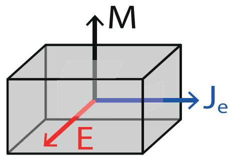
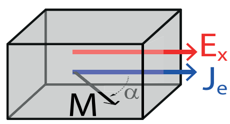
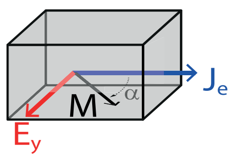
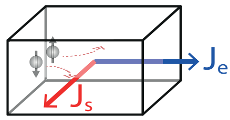
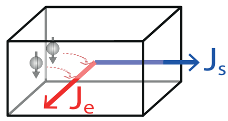
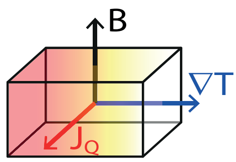
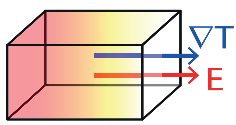
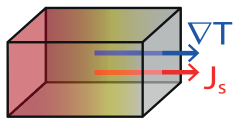
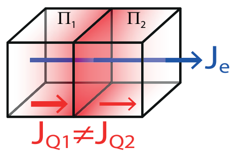
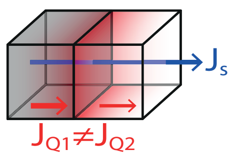
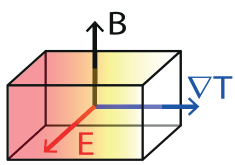
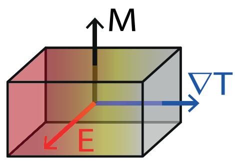
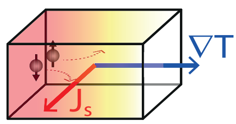
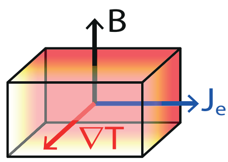
[1]The sign of the resulting vector, as drawn in the figures in red, is arbitrarily chosen, as it depends on specific material parameters such as, for example, the type of charge carrier and the spin-Hall angle. For the Lorentz force related effects, the direction of deflection of a charge q with a velocity $\vec{v}$ is given by $q(\vec{v} \times \vec{B})$

Name	**Description**	**Equation**	**Schematic**
Hall effect	Generation of a potential difference (voltage) due to the combination of an applied magnetic field perpendicular to a charge-current, leading to a Lorentz force on the electrons.	$\vec{E} \propto \vec{B} \times \vec{J}_e$	
Anomalous Hall effect (AHE)	Hall effect due to magnetization in the material. No external magnetic field needed.	$\vec{E} \propto \vec{M} \times \vec{J}_e$	
Anisotropic magneto-resistance (AMR)	A change in longitudinal resistance of a magnetic material, dependent on the angle α between the applied charge-current and the in-plane magnetization direction. The change in resistance is caused by spin-orbit interactions in the magnetic material.	$\vec{E} \propto (\vec{M} \cdot \vec{J}_e)\vec{M}$ $E_x \propto \cos^2 \alpha$	
Planar Hall effect (PHE)	Analogous to AMR; the PHE is defined as the transverse resistance change, which is dependent on the angle α between the applied charge-current and the in-plane magnetization direction. Therefore the PHE could also be named as transverse AMR.	$\vec{E} \propto (\vec{M} \cdot \vec{J}_e)\vec{M}$ $E_y \propto \cos \alpha \sin \alpha$	

Name	Description	Equation	Schematic
Spin-Hall effect (SHE)	By spin-orbit interactions, a charge-current sent through a material induces a transverse pure spin-current. No external magnetic field needed.	$\vec{J}_s \propto \vec{\sigma} \times \vec{J}_e$	
Inverse spin-Hall effect (ISHE)	Reciprocal effect of the SHE. Here a pure spin-current results in a transverse charge-current.	$\vec{J}_e \propto \vec{\sigma} \times \vec{J}_s$	
Thermal Hall effect (Righi-LeDuc effect)	Thermal analogue of the Hall effect. A temperature gradient in combination with a perpendicular magnetic field gives rise to a perpendicular heat flow caused by the Lorentz force.	$\vec{J}_Q \propto \vec{B} \times \vec{\nabla} T$	
Seebeck effect	The conversion of a temperature gradient into an electrical voltage, by electrons moving from the hot side to the cold side of the material.	$\vec{E} \propto \vec{\nabla} T$	

Name	**Description**	**Equation**	**Schematic**
Spin-(dependent-) Seebeck effect (SSE)	Analogous to the Seebeck effect: The generation of a spin-current (SdSE) or spin waves (SSE) by the presence of a temperature gradient in a magnetic material. The SdSE is caused by the spin-dependency of the Seebeck coefficient in a magnetic material.	$\vec{J}_s \propto \vec{\nabla} T$	
Peltier effect	Heating or cooling of a junction of two dissimilar materials ($\Pi_1 \neq \Pi_2$) when a charge-current is sent through. Reversing the current direction changes from heating to cooling.	$\vec{J}_Q \propto \vec{J}_e$	
Spin-(dependent-) Peltier effect (SPE)	As the Peltier effect, only with a pure spin-current. The junction needs to include a magnetic material at one side, as the heat-conductivity of a magnetic material is spin-dependent, resulting in an accumulation or expulsion of heat at the interface.	$\vec{J}_Q \propto \vec{J}_s$	
Nernst effect	An electric field induced in a conductive material by a temperature gradient and a perpendicular magnetic field. Caused by the Lorentz force.	$\vec{E} \propto \vec{\nabla} T \times \vec{B}$	

Name	**Description**	**Equation**	**Schematic**
Anomalous Nernst effect (ANE)	Nernst effect caused by the magnetization in the material itself. No external magnetic field needed.	$\vec{E} \propto \vec{\nabla} T \times \vec{M}$	
Spin-Nernst effect (SNE)	Similar to the spin-Hall effect, where the charge-current is replaced by a temperature gradient, which results in the generation of a pure spin-current. Also caused by spin-orbit interactions.	$\vec{J}_s \propto \vec{\nabla} T \times \vec{\sigma}$	
Ettingshausen effect	Inverse of the Nernst effect. A temperature gradient induced by an applied charge-current in the presence of a perpendicular magnetic field, caused by the Lorentz force.	$\vec{\nabla} T \propto \vec{B} \times \vec{J}_e$	
Thomson effect	Generation of extra heating (or cooling) of a material by sending a charge-current through it when a temperature gradient is present. Caused by the temperature dependence of the Seebeck coefficient. Here, $\dot{q}$ is the heat production rate per unit volume.	$\dot{q} \propto \vec{J}_e \cdot \vec{\nabla} T$